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Effect of thermal cycles on rock cliff deformation. Monitoring and interpretation

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Abstract. Climatic actions are one of the factors controlling the evolution of slopes, this paper is devoted to a specific effect, relatively little studied, related to the effect of climate-driven temperature changes on rock massif deformation. The particularity of the study is to focus on permeable rocks and Temperatures varying in a range which discards freeze/thaw effects. Research has been carried out in relation with the analysis of the real case of a limestone cliff located in the Périgord region, the massif was highly instrumented, results show a slow cyclic accumulation of deformations with time, essentially synchronic with thermal cycles. An advanced constitutive model, specifically developed to capture rock degradation due to the differential expansion of the main minerals composing the rock, has been developed. It has been calibrated on experimental results obtained in the laboratory on block samples tested in a climatic chamber for a long series (several months) of daily thermal cycles. Deformation and shear wave velocity were monitored during the test. Model shows a good agreement with laboratory measurements.

1. Introduction

Under cyclic changes in temperature, rock massifs experience expansion/contraction cycles that cause continuous stress redistribution in the zone of propagation and retrieval of the heat front. Because the amplitudes of temperature changes under climatic actions are moderate and it is generally considered that their maximum and minimum values were already reached during rock slope history, stress changes are in most cases expected to produce recoverable deformations. Observations evidence however that slow rock degradation may occur during this process [1–3]. It is usually attributed to processes of decohesion and microcracking caused by increase of stress intensity at grain contacts, resulting from the differential thermal expansion between minerals constituting the rock. This mechanism is mostly influenced by grain arrangement and minerals thermal expansion coefficient [3,4]. It may be at the source of degradation of rock mechanical properties like elastic moduli, tensile strength or uniaxial compression strength [5, 6] and may culminate into the propagation of discontinuities into the rock by microcracks coalescence.

The numerical modelling of this problem can be tackled by a continuum approach by idealizing the rock as a material provided with degradation laws for its mechanical properties. These laws aim at representing the macroscopic effect of grain decohesion, fissuration and, more generally, all types of



microstructure degradation [6]. This approach has been widely used for the modelling of microcracking phenomena in quasi-brittle materials, like rocks [7] or concrete [8]. These materials share common characteristics like heterogeneity due to the presence of different components and reduction in stiffness and strength due to microcracks development. Damage theory is the main tool used for this type of analysis. It consists in considering an irreversible degradation of stiffness parameters according to the evolution of the density of microcracks.

The work presents an advanced constitutive model allowing to represent rock degradation due to the differential thermal expansion of two different mineral phases. Model is applied to laboratory test carried out within the analysis of instabilities monitored in a cliff located in southern France, where temperature variations appear to be the main controlling factor. The case is first presented, then the numerical model and its validation on experimental laboratory tests described.

2. La Roque Gageac

La Roque Gageac is a small town located at the south-west of France at the bank of La Dordogne river in a regional area denominated The Périgord noir. The town is located at the toe of a 100 m high limestone cliff, and has been subjected to several rock falls events, last one occurred in 2010 when the roof of a troglodyte cavern (Figure 1) collapsed.

The 2010's event led to the installation of an instrumentation system, composed by jointmeters, extensometer and rock temperature measurements. Meteorological variables have been also monitored. Figure 2 presents a scheme of the instrumentation set-up. Detailed description of the devices are presented in [9–11], together with measurements interpretation.

10 years of continuous survey have evidenced the key role play by temperature variations in rock response. Figure 3 presents measurements of air temperature and differential displacements registered by the extensometer D2, see Figure 2. They evidence a close correlation: curves relating temperature to displacement draw an almost closed loop during one year. Over several years, they however evidence a slow accumulation of irreversible displacement.

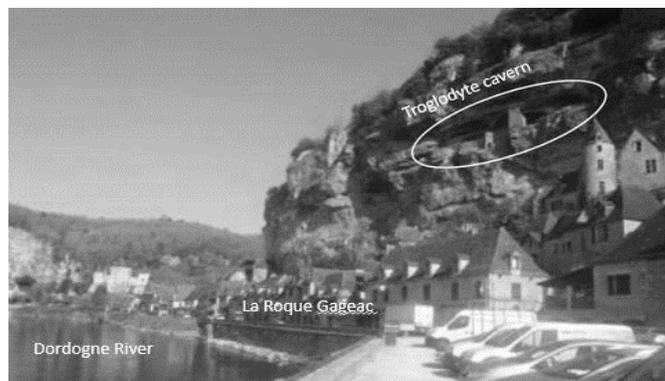


Figure 1. La roque Gageac town.

3. Experimental program

In order to evaluate the possible damage induced by natural thermal cycles in the limestone from La Roque Gageac, an experimental program has been developed. Two types of samples have been tested: one taken from a block felt from the roof of the cavern (labeled B) and others directly drilled at the face of the cliff in two different directions: parallel and perpendicular to the cliff's face (labelled CV and CH, respectively). Samples are cylindrical.

Samples were subjected to daily thermal cycles between 10°C to 50°C during 3 years, which represent more than 900 thermal cycles [12]. Samples degradation was followed by a measurement of deformations, elastic wave propagations and the uniaxial compression strength.

Deformation was measured using strain gauges in radial and axial direction during the whole test period. Measurements evidence an almost reversible strain during one thermal cycle, but an

appreciable accumulation between the start and the end of the series [9,12] (see for example strain time evolution shown in Figure 4 on samples B3 and CH2). Accumulation results in sample expansion for sample B3 and compression for sample CH2. Similar results are obtained for other samples.

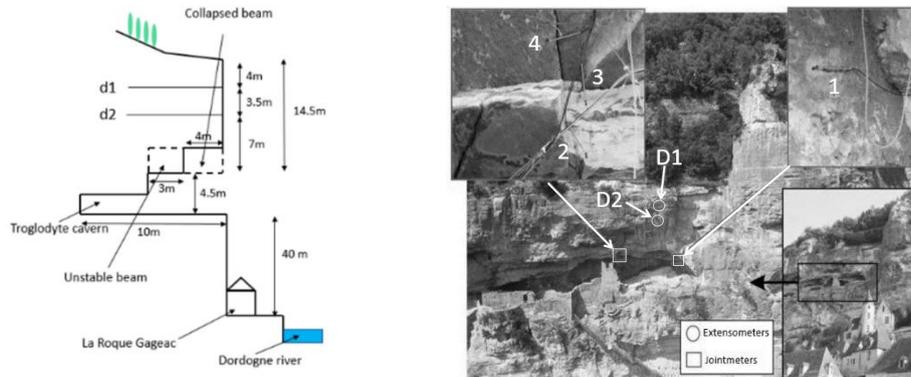


Figure 2. Instrumentation system.

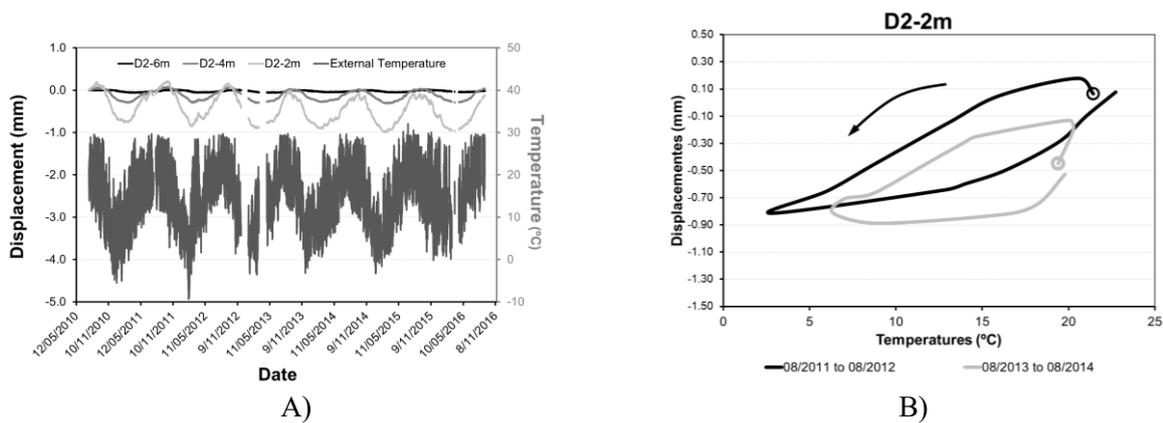


Figure 3. Extensometers and temperature relationship: A) extensometers and temperature measurements; B) Displacement accumulation D2-2m.

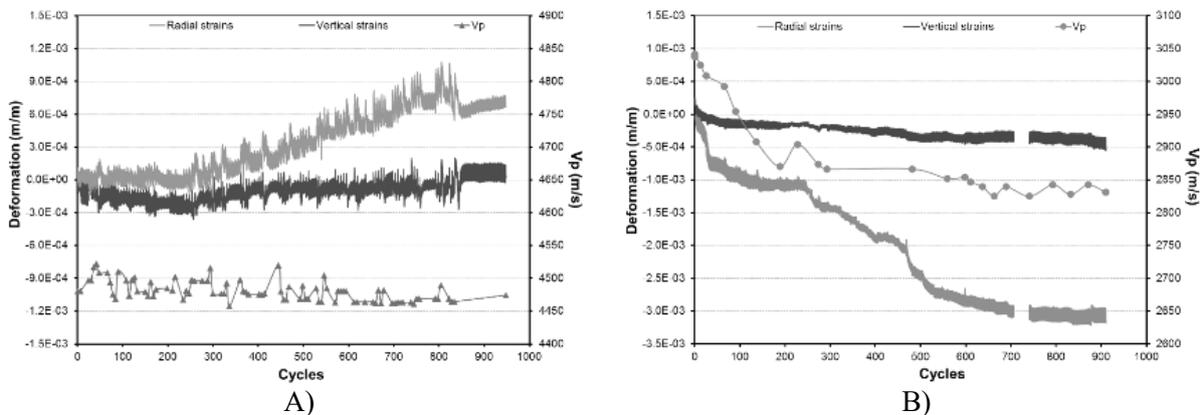


Figure 4. Strains and Vp evolution: A) Sample B3, B) Sample CH2.

Time evolution of elastic wave propagation velocity (EWPV) has been also followed during the test. EWPV is a parameter sensitive to the presence of defects on the samples, like internal fissures, and provides as such a good indicator of rock damage [13,14]. In all the tests, a reduction in the P-

wave propagation velocity was observed (see Figure 4 for the case of sample B3 and CH2). This fact strongly indicates the existence of processes of generation and propagation of micro or macro fissures in the rock.

It was moreover observed that EWPVs exhibited different evolution depending on the original location of samples in the cliff. Block samples (B) shows a slightly Vp reduction, around 4 %, however the variation for samples obtained from the cliff (C) is almost 8%. Similar results are obtained for the S-wave propagation velocity. An explanation to that could be related to the mineralogy of the samples. Mineralogical analyses indicated that samples obtained from the felt block were mainly composed by calcite, while samples drilled from the cliff presented a composition of almost 50/50 of calcite and quartz. This suggests that damage could be enhanced by the presence of two mineral phases in same amount within the rock, as the result of the development of internal stresses due to differential thermal expansion of calcite and quartz grains.

Another illustration of the same effect is presented in figure 5, which shows the evolution of the bulk modulus K with the number of thermal cycles (for comparison purposes, K is normalized by its initial value K0). K has been calculated from EWPV using the elastic theory. Curves of samples taken from the block (B3 and B7) show only a slight reduction in stiffness (between 1 and 5%) while the ones of the cliff samples exhibit a reduction up to 25%.

Uniaxial compressive strength (UCS) test was performed on 15 block samples (B) subjected to different number of thermal cycles. Figure 6 show the decrease of UCS with the applied number of cycles. This measurement can be favorably compared with the decrease of EWPV between its initial value and the value measured for the same of cycles. This indicate that the damage process affect both elastic properties and strength.

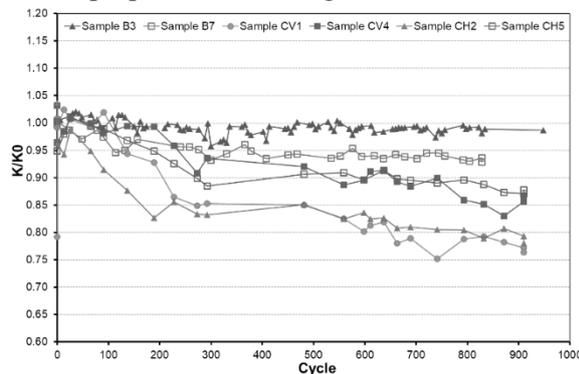


Figure 5. Bulk modulus evolution.

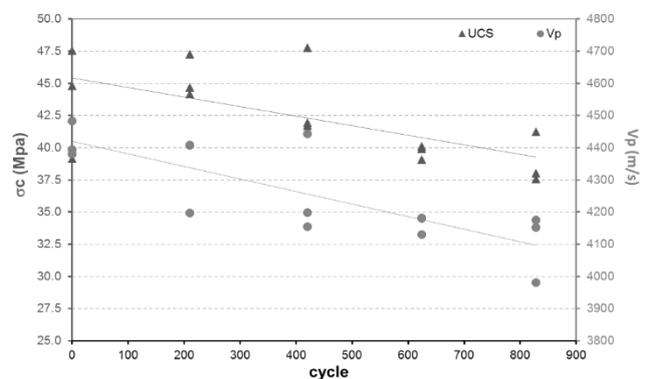


Figure 6. UCS and VP evolution

4. Numerical modelling

Experimental results evidenced that La Roque Gageac's limestone is susceptible to experienced mechanical damage under thermal cycles whose amplitudes are in the range of daily atmospheric variations. Interpretation of the measurements suggests a degradation mechanism enhanced by the presence of two mineral phases with different thermal expansion. Because of this heterogeneity, there is a build-up of internal stresses during thermal loading, resulting on local material weakening, fissuration or micro-cracking. The same effect has been forwarded by [14] in material with a single mineral phase, as the result of heterogeneity in grain or crystal shape and orientation.

Numerical modelling of this phenomenon was considered at macroscale by idealizing the rock as a continuum provided with degradation laws for its mechanical properties. These laws aim at representing the macroscopic effect of grain decohesion, fissuration and, more generally, all types of microstructure degradation.

4.1. Constitutive model

A macroscale law based on the behavior of a two-minerals rock skeleton has been developed, following the schema presented in Figure 7. It is a porous composite material whose skeleton is

composed by two minerals, labeled respectively 1 and 2. Each mineral k is provided with its own volume (V_k), strain (ε_{ij}^k) and stress (σ_{ij}^k) components. V_V denotes the volume of pores, $V_s = V_1 + V_2$ the volume of solid phase and $V = V_V + V_s = V_V + V_1 + V_2$ the total volume of the composite material. $e = V_V/V_s$ is the void ratio of the material.

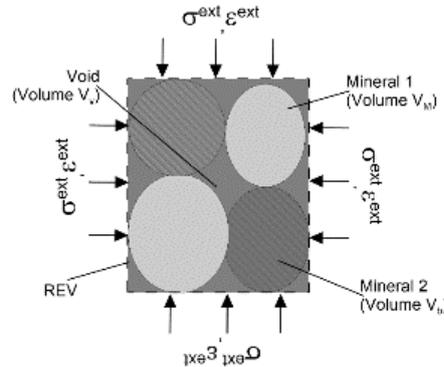


Figure 7. Conceptual scheme for the composite material constitutive model.

Different volumetric strains can be defined:

Internal volumetric strain $d\varepsilon_v^{int}$
(change in pore volume by unit volume of material)

$$d\varepsilon_v^{int} = -\frac{dV_V}{V} = -\frac{de}{1+e} \quad (1)$$

Volumetric strain of mineral phase 1

$$d\varepsilon_v^1 = -\frac{dV_1}{V_1} \quad (2)$$

Volumetric strain of mineral phase 2

$$d\varepsilon_v^2 = -\frac{dV_2}{V_2} \quad (3)$$

Volumetric strain of rock

$$d\varepsilon_v^{ext} = -\frac{dV}{V} \quad (4)$$

From mass conservation, the different volumetric strains are related by ($C_1 = V_1/V$ and $C_2 = V_2/V$ are mineral volume concentrations). This relationship is further extended to all strain components.

$$dV = dV_V + dV_1 + dV_2 \rightarrow d\varepsilon_v^{ext} = d\varepsilon_v^{int} + C_1 d\varepsilon_v^1 + C_2 d\varepsilon_v^2 \quad (5)$$

Internal strains are supposed to be related to by two kinematical restrictions:

$$X_{ij}^1 = \frac{c_1 d\varepsilon_{ij}^1}{d\varepsilon_v^{int}} \quad (6)$$

$$X_{ij}^2 = \frac{c_2 d\varepsilon_{ij}^2}{d\varepsilon_v^{int}} \quad (7)$$

where X_{ij}^1 and X_{ij}^2 are two tensor functions describing the internal redistribution of strains within the material and depends therefore on microstructural factors. These coefficients are considered as descriptors of rock microfabric at a given state of damage. For the sake of simplicity, they are taken isotropic: $X_{ij}^1 = X_1 \delta_{ij}$ and $X_{ij}^2 = X_2 \delta_{ij}$.

Most of thermal induced damage often traduces into decohesion of the interface between the two mineral phases and apparition of fissures. Within the two-mineral phase scheme contemplated in this work, interface is not explicitly represented and the degradation mechanism must be assigned to one of the phases. Since both mineral phases play a symmetric role in (5), it can indistinctively allocate to phase 1 or 2. By convention, phase 2 has been chosen to carry the interface response.

It is moreover expected that part of the load carried by the interface between the two mineral phases (and thus by phase 2 in the model) is transferred to the matrix when phase 1 degrade, leading to

a decrease in the value of X_1 . To account for this effect, coefficient X_2 is set as a function of damage variable L .

According to this scheme, thermal loading will cause change in volume of mineral phases, which are not necessarily compatible with the external strain applied to the medium. Mechanical strains will then develop inside each phase to adapt the change in volume, which will in turn change the stresses in the mineral phases, leading to possible material degradation even in absence of external loads. Using Eq. (3), (4), (6) and (7), mineral phase strain increments are related to the external one by:

$$d\varepsilon_{ij}^1 = \frac{X_1/c_1}{1 + X_1 + X_2} d\varepsilon_{ij}^{ext} = b_1 d\varepsilon_{ij}^{ext} \quad (8)$$

$$d\varepsilon_{ij}^2 = \frac{\frac{b_1}{X_2/c_2}}{1 + X_1 + X_2} d\varepsilon_{ij}^{ext} = b_2 d\varepsilon_{ij}^{ext} \quad (9)$$

The behavior of each component, matrix and bond, is represented by its own constitutive law. Mineral 1 is provided with a non-degrading linear cross-anisotropic thermo-elastic law. Mineral 2, which carries the effect of degradation interface, is provided with the damage model proposed by Carol et al [15] and enhanced with temperature.

Stress for the composite material is obtained by stating that the work input into the medium under any compatible external strain increment is equal to the sum of the work input into mineral phase 1 and 2. Labelling σ_{ij}^{ext} , σ_{ij}^1 and σ_{ij}^2 the stresses acting on the composite medium and mineral phases respectively, external stress can be defined as:

$$\sigma_{ij}^{ext} = \frac{X_1}{1 + X_1 + X_2} \sigma_{ij}^1 + \frac{X_2}{1 + X_1 + X_2} \sigma_{ij}^2 \quad (10)$$

In this framework, stress and strain of each phase are related through their own constitutive law.

$$d\sigma_{ij}^1 = D_{ijkl}^1 d\varepsilon_{kl}^1 \quad (11)$$

$$d\sigma_{ij}^2 = D_{ijkl}^2 d\varepsilon_{kl}^2 \quad (12)$$

And the constitutive law of the composite material reads:

$$d\sigma^{ext} = (c_1 b_1^2 D^1 d\varepsilon^{ext} + c_2 b_2^2 D^2) d\varepsilon^{ext} + \sigma^1 d(c_1 b_1) + \sigma^2 d(c_2 b_2) \quad (13)$$

4.2. Numerical modelling results

Mineralogical composition analysis performed on samples from La Roque Gageac shows that this limestone is mainly composed by calcite and quartz. In this work, the degradation mechanism at mineral boundaries is assigned to the calcite which will thus be considered as mineral phase 2. Mineral phase 1 correspond to quartz.

Six tests have been modelled: two of them were performed on samples extracted from fallen blocks (B3 and B7) and four on samples obtained from boreholes drilled from the cliff face (CV4, CV5, CH2 and CH3). CV4 and CV5 cored in the vertical direction, CH2 and CH3 in the horizontal one.

The parameters considered for material are listed on Table 1. They include physical properties: volumetric fraction of voids (porosity) and concentrations of mineral phase 1 (c_1) and 2 (c_2). Values vary from sample to sample, according to the measurements obtained in the laboratory.

In order to reduce the number of parameters to estimate, it has been considered that mineral phase 1 and 2 are provided with the same thermal expansion coefficient. Under this assumption, the thermal coefficient was obtained for each sample from the external strains measurements. It is important to point out that, according to test results, thermal expansion coefficient has been considered anisotropic and two different values have been defined for the axial and radial directions.

Bulk modulus of quartz and calcite phases are taken from the typical values presented by Carmichael, 1989 [16]. Once fixed K_1 , K_2 , c_1 and c_2 for each sample, X_1 and X_2 values were back-analysed from the measurements of initial rock bulk modulus taken into account the restrictions provided by Hashin & Shtrikman bounds [17].

Table 1. Parameters used for the numerical modelling of experimental results.

| | | Sample B3 | Sample B7 | Sample CV4 | Sample CV5 | Sample CH2 | Sample CH3 |
|--------------------|--------------------------|-----------|-----------|------------|------------|------------|------------|
| Mineral phase 2 | K_{10} (MPa) | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| | r_1 | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 |
| | r_0 | 1e-5 | 1e-5 | 1e-5 | 1e-5 | 1e-5 | 1e-5 |
| Mineral phase 1 | K_1 (MPa) | 35000 | 35000 | 35000 | 35000 | 35000 | 35000 |
| | ϕ'_1 | 30 | 30 | 30 | 30 | 30 | 30 |
| | c'_1 (MPa) | 46 | 46 | 46 | 46 | 46 | 46 |
| Composite material | Density γ (kg/m3) | 2340 | 2340 | 2340 | 2340 | 2340 | 2340 |
| | Porosity | 0.12 | 0.18 | 0.2 | 0.2 | 0.18 | 0.17 |
| | c_1 | 0.78 | 0.72 | 0.4 | 0.5 | 0.41 | 0.415 |
| | c_2 | 0.1 | 0.1 | 0.4 | 0.3 | 0.41 | 0.415 |
| | X_1 | 1.1 | 0.67 | 0.23 | 0.23 | 0.24 | 0.35 |
| | X_2 | 0.28 | 0.3 | 0.52 | 0.32 | 0.49 | 0.61 |

For the modeling of block samples (mainly composed by calcite), coefficient X_2 and c_2 has been taken higher than coefficient X_1 and c_1 and material bulk modulus is mainly controlled by phase 2. Conversely, values of X_1 higher than X_2 have been assigned to cliff samples while c_1 has been taken equal to c_2 . In that case, composite material bulk modulus is governed by the mineral phase 1 stiffness.

Samples were modelled as a material point, therefore, temperature variations are imposed to all the nodes considered, corresponding to a quasi-steady state heating process. Figure 8 presents the evolution of the computed rock bulk modulus. They compared favourably with the evolution obtained from test results for all the samples.

Numerical model is capable to reproduce the slight degradation of bulk modulus observed on B samples and the more dramatic evolution observed on CH and CV samples. This confirms the importance of considering the calcite as the damageable material in these tests.

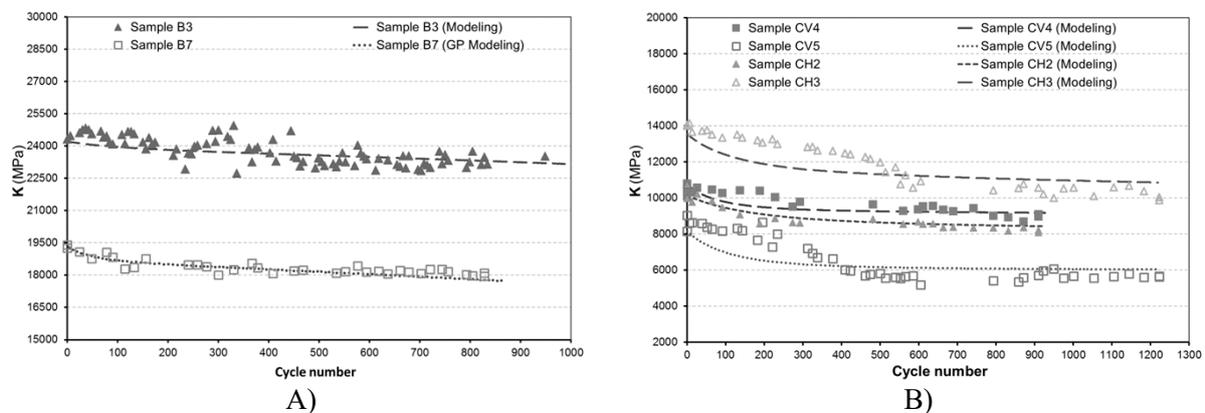


Figure 8. Modelling results A) samples obtained from felt blocks B) samples cored at the cliff face.

5. Concluding remarks

Natural thermal variations may induce internal stresses in rock massifs which can lead to generation of internal microfissuration and degradation of the rock. The experimental program developed on the calcareous rock from La Roque Gageac shows that thermal cycles between 10 to 50 degrees induced a strength reduction and a possible internal microfissuration. This response is mainly attributed to the mineralogical composition of the rock, made of calcite and quartz, two minerals with different thermal properties. A composite material constitutive model is proposed in order to reproduce this phenomenon, showing appropriate agreement between laboratory results and numerical simulations.

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